Herbage mass, nutritive value and canopy spectral reflectance of bermudagrass pastures

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Abstract

Timely and accurate detection of above-ground herbage mass and the nutritive value of pastures can help the more efficient adjustment of stocking rate and determine the timing of protein supplements to be fed to livestock grazing these pastures. The objectives of this study were to determine seasonal variation in herbage mass, neutral-detergent fibre (NDF), acid-detergent fibre (ADF) and crude protein (CP) concentrations of herbage and canopy reflectance of pastures of genotypes of bermudagrass (*Cynodon dactylon* L.), and to analyse the relationships between these descriptors of nutritive value of herbage and canopy reflectance in broad spectral wavebands. Three bermudagrass pastures of varieties Midland and Ozarka, and an experimental hybrid, 74 × 12-12, were established in 1991 and had received the same field management and stocking rate. Canopy reflectance, above-ground herbage mass of DM and CP, and NDF, ADF and CP concentrations of herbage were measured in the growing seasons of 2002 and 2003. Year, genotype and sampling date significantly ($P < 0{\cdot}05$) affected most measured variables. Ratios of canopy reflectance in blue to red ($R_{(blue)}/R_{(red)}$) and in near infrared to red ($R_{(NIR)}/R_{(red)}$) wavebands were highly correlated with concentrations of CP in herbage and herbage mass of CP but the relationships between reflectance ratios and NDF and ADF concentrations of herbage were relatively low. It is concluded that the CP concentration of herbage and herbage mass of CP of pastures can be estimated throughout the growing season using remote sensing of canopy reflectance and the information may be used for pasture and livestock management.

Keywords: crude protein, neutral-detergent fibre, acid-detergent fibre, plant genotypic variation, canopy reflectance, reflectance ratios

Introduction

Grazing lands and pastures are important components in agricultural production systems because they not only provide feed for livestock but also replenish soil organic matter, prevent soil erosion and restore soil fertility (Fageria *et al.*, 1997). Pasture productivity and nutritive value are major factors that determine patterns of grazing distribution of wildlife and livestock (Bailey *et al.*, 1996). Adequate nutritive value of herbage is essential for a high rate of liveweight gain and overall livestock performance (Ball *et al.*, 2001). Above-ground herbage mass production and measures of nutritive value, such as crude protein (CP), neutral-detergent fibre (NDF) and acid-detergent fibre (ADF) concentrations, and *in vitro* digestibility of dry matter (DM), vary between years and between plant growth stages within a given growing season (Ball *et al.*, 2001). Accurate information on plant N status of pastures, herbage mass of DM, and nutritive value of herbage is extremely useful in livestock and forage management. Better understanding of factors, such as genotypes and environmental conditions, which influence seasonal patterns of herbage mass and nutritive value, and timely prediction of these variables, can help improve decision-making by grazing land managers on, for example, the adjustment of stocking rates.

Analysis of the nutritive value of herbage mainly includes determination of DM digestibility, and NDF, ADF and CP concentrations (Ball *et al.*, 2001). Traditional laboratory chemical methods, used to determine these variables, are time-consuming and costly, and generate hazardous waste that must be disposed of. Relative to chemical procedures, near-infrared

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reflectance spectroscopy (NIRS) analysis provides rapid, accurate and less expensive estimates of the nutrient composition of herbage (Marten *et al.*, 1989; Shenk and Westerhaus, 1994), and has been widely used for the analysis of the nutritive value of forages. Although NIRS has great advantages compared with laboratory chemical methods, it still requires the collection and preparation of vegetation samples. To date, only a limited number of studies have been conducted to determine if the nutritive value of herbage can be predicted *in situ* using non-destructive, remotely sensed measurements of reflectance spectral features of the pasture canopy.

Recent advances in remote sensing allow the collection of timely reflectance data from leaf to landscape scales. The information from remote sensing has been used to assess and predict land coverage, to detect plant stresses and to estimate crop growth and yield. Studies have found close relationships between plant physiological variables and spectral reflectance of leaves and canopies (Chappelle *et al.*, 1992; Peñuelas and Filella, 1998; Peñuelas and Inoue, 2000; Zhao *et al.*, 2003). Tueller (2001) reviewed the literature on pasture management with remote sensing and summarized that there was the potential to monitor herbage production and utilization through analysis of remotely sensed imagery.

A number of reflectance-based vegetation indices have been developed from multi- or hyper-spectral remotely sensed data and are used to monitor plant growth and physiological variables (Peñuelas and Filella, 1998; Roderick *et al.*, 2000). The simple ratio of reflectance in near infrared (NIR) to red regions ($R_{(NIR)}/R_{(red)}$) of the electromagnetic spectrum and the normalized difference vegetation index (NDVI), defined as $(R_{(NIR)} - R_{(red)})/(R_{(NIR)} + R_{(red)})$, are the most widely used indices in precision agricultural production (Gamon *et al.*, 1995; Peñuelas and Filella, 1998). The $R_{(NIR)}/R_{(red)}$ and NDVI are mainly used for predicting plant canopy coverage, leaf area index and herbage mass, and for detecting plant biotic and abiotic stresses. Information concerning relationships between the nutritive value of herbage of grazed pastures and plant canopy reflectance in broad wavebands, such as the Landsat Thematic Mapper (TM) bands, is limited. It is hypothesized that the $R_{(NIR)}/R_{(red)}$, NDVI or other broad waveband reflectance ratios, obtained from canopy reflectance measurements, can be used to non-destructively estimate above-ground herbage mass of DM, and NDF, ADF and CP concentrations, of herbage in grazing systems. To test this hypothesis and to determine genotypic variation among bermudagrasses (*Cynodon dactylon*, L.) for these variables, a 2-year experiment was carried out on three well-established bermudagrass pastures.

Materials and methods

Experimental location

The experiment was conducted at the USDA-ARS Grazinglands Research Laboratory, El Reno, OK, USA (Lat. 35°32′N, Long. 98°02′W) in 2002 and 2003. The experimental site is located in the Southern Great Plains of the USA and is characterized by level to slightly rolling topography. Average annual precipitation at the experimental site is 877 mm and the annual mean temperature is 15·0°C. The long-term rainfall distribution and monthly temperatures are presented in Figure 1. Two (in 2002) and three (in 2003) pastures of bermudagrass, a perennial warm-season C_4 species and widely used for pasture and hay in the Southern Great Plains and Southeastern areas of the USA, were selected for collection of herbage samples and canopy hyper-

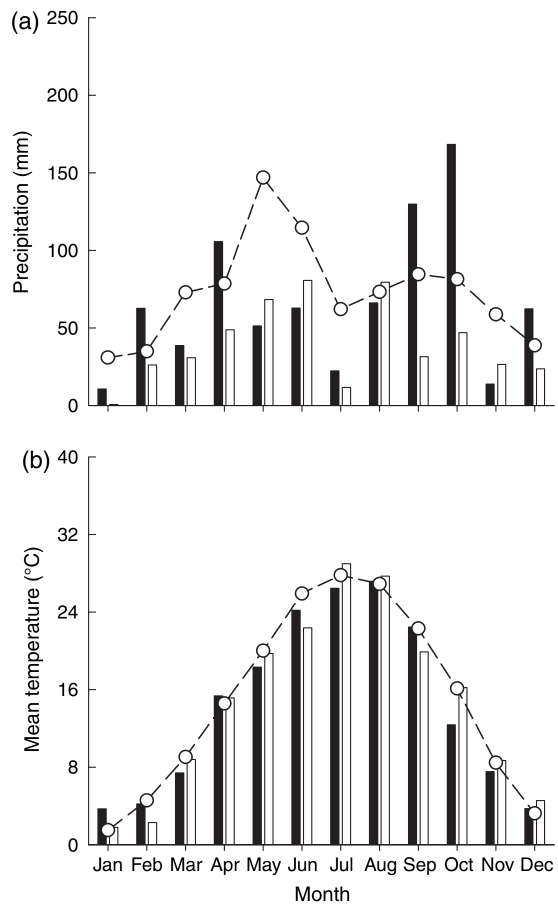

Figure 1 Monthly (a) accumulated precipitation and (b) mean air temperature at the experimental location in El Reno, OK, USA, in 2002 (■) and 2003 (□) as compared with the 30-year (1971–2000) average (○).

spectral reflectance data during the growing season. The soil type of the experimental fields was a Brewer silt clay loam (fine-loamy, mixed, thermic Udic Rhodustalfs). Bermudagrass pastures of varieties Midland and Ozarka, and an experimental hybrid (74 × 12-12), were established in 1991 with equal field size (3·2 ha) and received the same production management and stocking rate (3 steers ha^{-1}). Starting dates of grazing were 16 May in 2002 and 20 May in 2003. Fertilizer applications were based on soil test results and production recommendations for bermudagrass production with a urea-N fertilizer rate of 77 kg N ha^{-1} in 2002 and 67 kg N ha^{-1} in 2003 at the start of the growing season (late April to early May). Each field was split into eight plots (≈0·4 ha in size) for canopy reflectance measurements and sampling.

Measurements

In early, mid-, and late growing season (2002) or six times throughout the growing season on 12 June, 19 June, 27 June, 3 July, 11 July and 5 September (2003) when plant canopy completely covered the ground, canopy reflectance measurements were made during clear days between 1000 and 1200 h (Central Standard Time) from all plots of each genotype. A portable FieldSpec FR spectroradiometer[1] (Analytical Spectral Devices Inc. (ASD), Boulder, CO, USA), which measures spectral reflectance in the 350–2500 nm wavelength range, was used to collect the canopy reflectance data. The optical sensor of the spectroradiometer was mounted on a boom 2 m above and perpendicular to the soil surface. The radiometer had a 25° field-of-view (FOV), producing a view area with a 0·89 m diameter. A Spectralon (Labsphere, Inc., Sutton, NH, USA) reference panel (white reference) was used to optimize the ASD instrument prior to taking three canopy reflectance measurements in each plot. The canopy reflectance data were expressed as relative values by dividing them by the white reference panel reflectance readings.

After the reflectance measurements, all vegetation in a 0·25-m^2 area within the ASD FOV was clipped within 1 cm of the ground surface. Additional vegetation samples were collected on 23 July, 7 August and 21 August in 2003 to determine seasonal patterns of herbage mass and nutritive value, but reflectance measurements were not made on these dates because of unavailability of the spectroradiameter. Plant samples were immediately dried in a forced air oven at 65°C for 72 h, weighed and ground for determinations of NDF, ADF and nitrogen (N) concentrations. Quantification of NDF and ADF were based on standard laboratory procedures as outlined on the Ankom Technology (Fairport, NY, USA) web site (http://www.ankom.com/09_procedures/procedures.shtml). Nitrogen concentration was determined using an automated combustion instrument (LECO Corp., St Joseph, MI, USA). CP concentration of herbage was calculated by multiplying the N concentration by 6·25 (Pearson and Ison, 1987). Herbage mass of CP (kg ha^{-1}) was estimated by multiplying total herbage mass of DM by the CP concentration of the herbage.

Data analysis

Because limited measurements were taken and the pasture of the hybrid genotype 74 × 12-12 was not measured in the growing season of 2002, only the Midland and Ozarka data from three sampling dates (early, mid- and late season) were used in the statistical analysis to determine the effect of genotype on the nutritive value as affected by sampling date and year. Measured NDF, ADF and CP concentrations, herbage mass of DM and CP at selected dates for the Midland and Ozarka pastures were subjected to analysis of variance using PROC GML procedures (SAS Institute Inc., 1997).

Reflectance values in four wavelength ranges (i.e. 350–399, 1350–1449, 1700–1969 and 2300–2500 nm) were first omitted from the reflectance data sets because of instrument noise or location of these bands within regions of atmospheric moisture absorption. The remaining reflectance data were averaged across 10-nm wavebands to decrease the amount of data for analysis, giving a total of 153 narrow wavebands between 400 and 2300 nm. The three canopy reflectance values measured in each plot at each sampling date were averaged. Analysis of variance indicated that the interactive effects of genotype, year and sampling date on canopy reflectance in most broad wavebands were not significant. Therefore, the reflectance data were averaged across all measuring dates within a genotype or across genotypes within a typical sampling date of early, mid-, or late seasons to determine main effects of genotypes, years and sampling dates on canopy spectral reflectance. Based on the Midland pasture or early season measurements, the proportional change in reflectance in all wavebands for other pastures or measuring dates was further calculated. Both the reflectance and the proportional changes in reflectance were plotted against wavelength.

To determine relationships between herbage masses of DM and CP, concentrations of NDF, ADF and CP and remotely sensed data in broad wavebands, the spectral

[1]Use of trade or product names is for informational purpose only and does not imply endorsement by the United States Department of Agriculture to the exclusion of any other product that may be suitable.

reflectance data were combined into six broad wavebands: blue (450–520 nm), green (520–600 nm), red (630–690 nm), near-infrared (NIR, 760–900 nm), short-wave infrared 1 (SWIR1, 1550–1750 nm), and short-wave infrared 2 (SWIR2, 2080–2300 nm), based on the Landsat TM bands (http://rst.gsfc.nasa.gov/Intro/Part2_20.html). Two commonly-used reflectance indices, $R_{(NIR)}/R_{(red)}$ and NDVI, and all combinations of two-band reflectance ratios, were also calculated. The measured nutritive value and corresponding reflectance data were pooled across years, genotypes, plots and sampling dates ($n = 144$). Pearson's correlation coefficients (r) between the measures of nutritive value and reflectance in each broad waveband and reflectance ratios were calculated. For each measure of nutritive value of herbage, the reflectance ratio having the greatest $|r|$ was selected and linear regression analysis of the reflectance ratio with the nutritive value of herbage was conducted.

Results

Precipitation and temperature

Total annual precipitation at the experimental location was 794 mm in 2002 and 475 mm in 2003, proportionately 0·10 and 0·46 less, respectively, than the 30-year (1971–2000) average of 877 mm (Figure 1a). Although the total precipitation in 2002 was close to the long-term average, precipitation was less during the key growth period of herbage from May to July. In 2003, monthly precipitation, except for August, was much less than the 30-year average. The annual mean air temperatures in 2002 (14·4°C) and in 2003 (14·7°C) were similar to the long-term average (15·0°C), but the monthly mean temperature in 2003 was 2·5°C lower in June, and 1·2°C higher in July, compared with the long-term average (Figure 1b). In general, the growing season in 2003 was drier and hotter than in 2002. The differences in precipitation and air temperatures between the two years may explain the between-year variations in pasture plant growth, development and nutritive value of the herbage.

Herbage mass of dry matter

Year and genotype significantly affected herbage mass of DM and the interactive effect of year × genotype on herbage mass of DM was also detected (Table 1). The herbage masses of DM in 2002 of Ozarka and Midland pastures (Figure 2a), when averaged across sampling dates, were similar (5120 and 4975 kg DM ha^{-1} respectively). Ozarka had the greatest and Midland the least herbage mass of DM among the three tested genotypes at most sampling dates in 2003 (Figure 2b) and, when averaged across sampling dates, Midland, Ozarka, and 74 × 12-12 pastures produced 2272, 4197, and 3911 kg DM ha^{-1} of herbage mass respectively. Above-ground herbage mass of DM in 2003 was less than that in 2002. The response of herbage mass of DM to the growth environments of the two years differed among the genotypes. In 2003, the Midland pasture produced 0·54 less herbage mass of DM than in 2002, while Ozarka produced 0·18 less herbage mass of DM in 2002 (Figure 2).

Nutritive value of herbage

In both years, concentrations of NDF and ADF of herbage increased slightly while CP concentration of herbage decreased as the growing season progressed (Figure 3). Year significantly affected NDF and CP concentrations, and genotype differences in ADF and CP concentrations were detected (Table 1). Sampling date significantly affected all the measures of nutritive value. Some interactive effects of year × genotype, year × sampling date and genotype × sampling date on NDF or CP concentration of herbage were also significant (Table 1). Overall, Ozarka pastures had slightly lower concentrations of NDF and CP of herbage than Midland pastures. Averaged across the sampling dates in 2002, the concentrations of NDF, ADF and CP of herbage were 714, 346 and 93 g kg^{-1} DM, respectively, for the Midland pasture and were 698, 344 and 86 g kg^{-1} DM, respectively, for the Ozarka pasture. In 2003, the NDF concentration of herbage of the three genotypes was similar (740 g kg^{-1} DM), averaged across the season, but

Table 1 Significance of each source of variation for the concentrations (g kg^{-1} DM) of neutral-detergent fibre (NDF), acid-detergent fibre (ADF), and crude protein (CP) in herbage and above-ground herbage mass of DM and CP (kg ha^{-1}) of two bermudagrass pastures (genotypes Midland and Ozarka) in the early, mid- and late growing seasons of 2002 and 2003

Source	df	NDF	ADF	CP	Herbage mass of DM	Herbage mass of CP
Year	1	***	ns	***	***	***
Genotype	1	ns	*	**	*	ns
Date of sampling	2	***	***	***	ns	***
Year × genotype	1	***	**	ns	*	ns
Year × date	2	ns	ns	**	ns	ns
Genotype × date	2	***	ns	ns	ns	ns

*, $P < 0.05$; **, $P < 0.01$ and ***, $P < 0.001$. ns, not significant ($P > 0.05$).

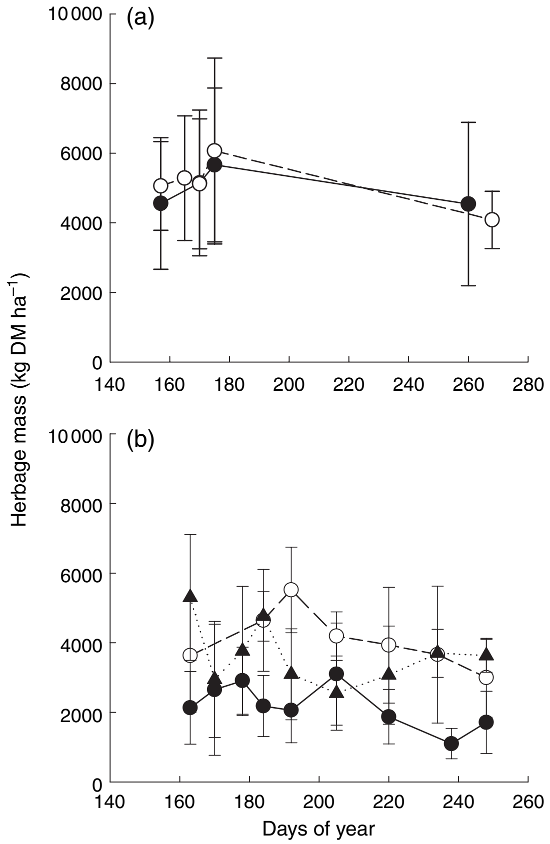

Figure 2 Above-ground herbage mass of DM of Midland (●), Ozarka (○), and 74 × 12-12 (▲) at different sampling dates in 2002 (a) and 2003 (b). Each data point represents the pasture mean (standard deviation of mean) of four to eight samples.

Ozarka had a proportionately 0·071 lower ADF concentration and 0·162 lower CP concentration of herbage than the Midland pasture. The pasture of genotype 74 × 12-12 had comparable NDF, ADF and CP concentrations of herbage to that of the Midland pasture. The ADF concentration did not differ but differences were detected in NDF and CP concentrations between the years within the genotype. In 2003, mean NDF concentration across the Midland and Ozarka pastures was 0·05 greater and mean CP concentration was 0·28 less than that observed in 2002. Averaged across sampling dates in the 2003 growing season, herbage masses of CP of the pastures of Midland, Ozarka and 74 × 12-12 were 161, 218 and 275 kg ha^{-1} respectively.

Canopy spectral reflectance

Canopy spectral reflectances in the 10-nm wavebands showed some differences between genotypes in both years (Figure 4a) and among sampling dates within each year (Figure 4c). Specifically, in both years the Ozarka pasture had a 0·10 greater reflectance at 545 nm and a 0·15 less reflectance around 685 nm than the Midland pasture when averaged across years (Figure 4b). Furthermore, the Ozarka pasture had greater reflectance in the near-infrared range (715–1145 nm) and less reflectance in short-wave infrared range (1500–2400 nm) compared with the other two genotypes (Figure 4b). As the plants aged, canopy reflectances increased in the visible (400–700 nm, with the greatest increase at 675 nm) and/or short-wave infrared (1500–2200 nm) ranges but decreased between 715 and 1300 nm when averaged across genotypes (Figure 4d).

Both reflectance indices, $R_{(NIR)}/R_{(red)}$ and NDVI, declined with time between early June and September (Figure 5). In 2002, the $R_{(NIR)}/R_{(red)}$ and NDVI values of the Midland and Ozarka pastures were similar over the growing season but some differences were observed among the three genotypes in 2003 (Figure 5). Averaged over the growing season, the $R_{(NIR)}/R_{(red)}$ and NDVI were both greater in 2002 than in 2003.

Relationships between nutritive value of herbage and canopy reflectance

Correlation coefficients (*r*) of single-band reflectance, $R_{(NIR)}/R_{(red)}$, and NDVI with the concentrations of NDF, ADF and CP in herbage, and herbage mass of DM and CP are presented in Table 2. The large data set ($n = 144$) made most *r* values statistically significant but reflectance in any single broad waveband and NDVI only explained 0·03 to 0·39 (i.e. small r^2 values) of the variation in most forage nutritive value parameters (except herbage mass of CP).

Compared with the reflectance in a single broad waveband, most two-band reflectance ratios, including $R_{(NIR)}/R_{(red)}$, improved the relationships between canopy broad-band reflectance and nutritive value of herbage with the greater $|r|$ values (data not shown). Of the all possible combinations of two-band reflectance ratios, the ratio of blue-to-red reflectance ($R_{(blue)}/R_{(red)}$) was most highly correlated with NDF ($r = -0{\cdot}48$) and CP ($r = 0{\cdot}71$) concentrations, while $R_{(SWIR1)}/R_{(RE)}$, $R_{(NIR)}/R_{(SWIR1)}$, and $R_{(NIR)}/R_{(red)}$ had the greatest $|r|$ with ADF concentration ($r = 0{\cdot}46$), herbage mass of DM ($r = 0{\cdot}68$) and herbage mass of CP ($r = 0{\cdot}82$) respectively ($n = 144$). All the *r*-values were statistically significant ($P < 0{\cdot}0001$). Among the five variables measured, CP concentration and herbage mass of CP had the strongest linear relationships with the corresponding reflectance ratios but the relationships of NDF and ADF with their reflectance ratios were much weaker (Figure 6).

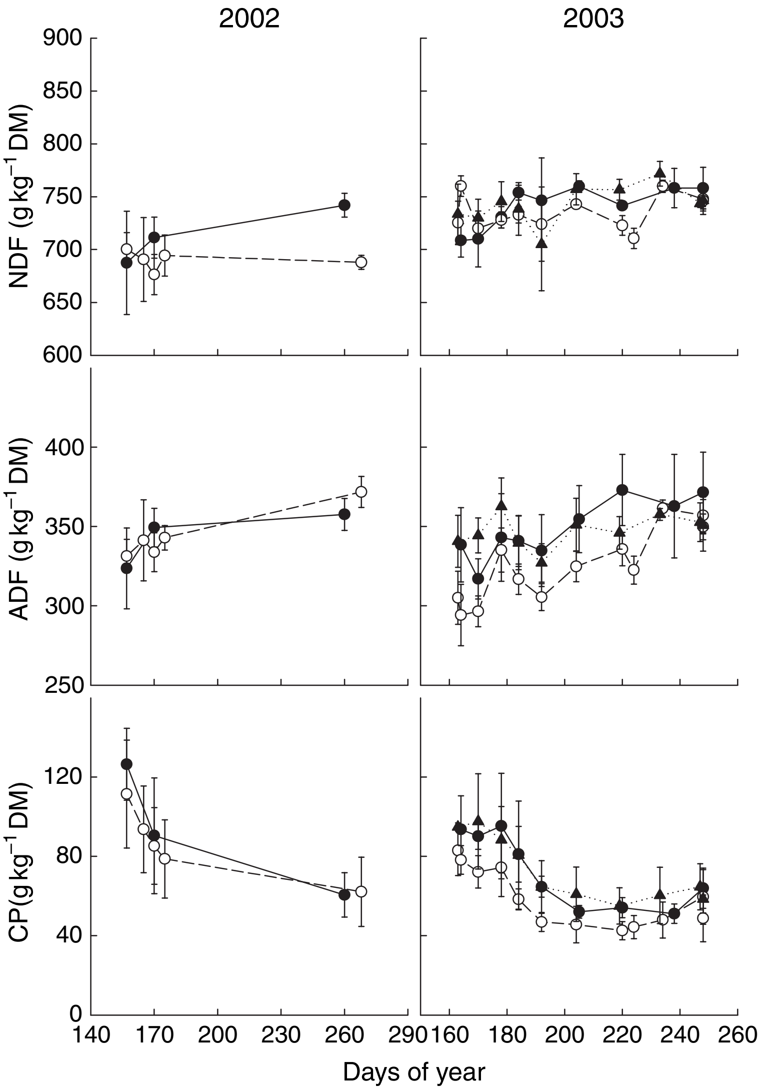

Figure 3 Time-series plots of neutral-detergent fibre (NDF), acid-detergent fibre (ADF) and crude protein (CP) concentrations by sampling date, growing season, and genotype. Three genotypes are Midland (●), Ozarka (○), and 74 × 12-12 (▲). Each data point represents the pasture mean (standard deviation of mean) of four to eight samples.

Discussion

The seasonal patterns of herbage mass of pastures used in this study differ from that of ungrazed plant communities because grazing animals consume plant parts as the plants are growing (Gardner *et al.*, 1985). Above-ground herbage mass and nutritive value of herbage in grazed bermudagrass pastures varied greatly between years (Figures 2 and 3). The differences in precipitation and air temperature (Figure 1) between the two years might explain the variations between years in herbage mass and nutritive value because they are closely related to these two climatic factors (Ball *et al.*, 2001). Roter and Kretschmer (1985) suggested that bermudagrass is more tolerant to drought environments than other grasses and that the requirement for minimum annual rainfall was about 500 mm. Precipitation in 2003 (475 mm) at the experimental location (Figure 1a) was less than the minimum value suggested by Roter and Kretschmer (1985). Therefore, less precipitation in April and July 2003 might be one of major factors causing a lower herbage masses and nutritive value compared with the results in 2002.

Similar to earlier reports by Taliaferro *et al.* (1995; 2000), and Ball *et al.* (2001), genotype differences in response to drought and high temperatures were clearly detected in the present study (Figure 2). In general, screening and utilization of genotypes with more tolerance to drought and high temperature can effectively reduce negative effects on grass productivity. The results indicated that the Ozarka pasture was more tolerant to the unfavourable environment in 2003 and

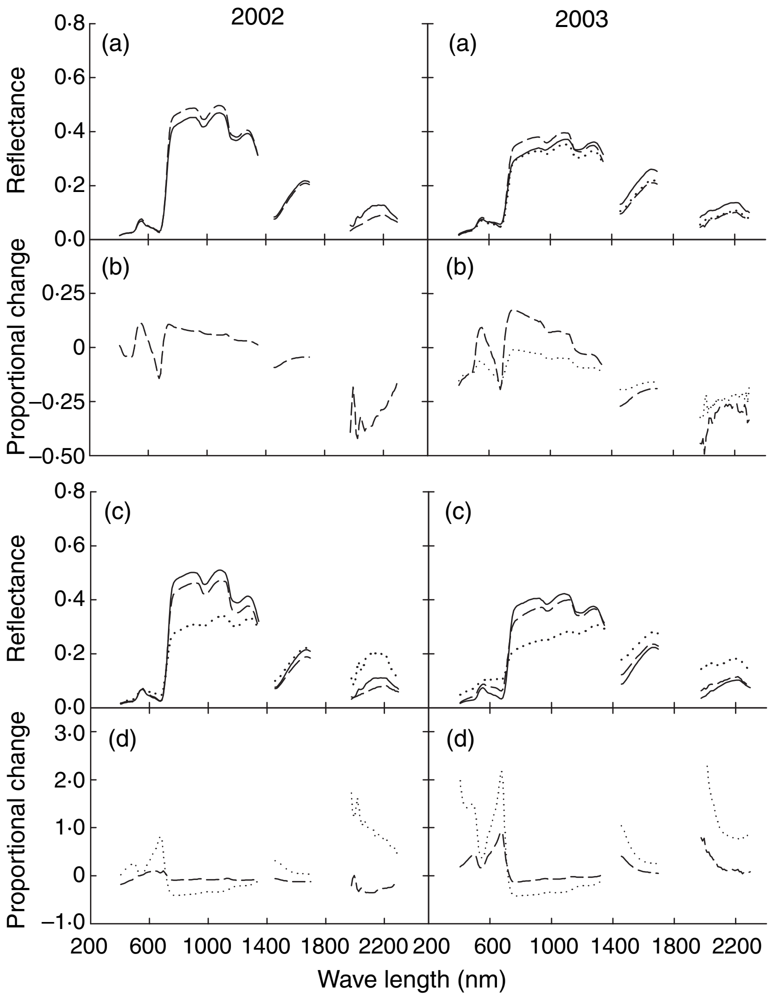

Figure 4 (a) Canopy reflectance averaged over sampling date for Midland (solid line), Ozarka (dashed line), and 74 × 12-12 (dotted line) pastures, (b) proportional difference in average canopy reflectance using the Midland pasture as the base value for Ozarka and 74 × 12-12, (c) canopy reflectance at early (solid line), mid- (dashed line), and late (dotted line) growing seasons and (d) proportional difference in canopy reflectance using the early growing season as the base value in 2002 and 2003.

produced more herbage mass than the other two genotypes.

Changes in the nutritive value of grazed bermudagrass pastures during the growing seasons in the present study are consistent with other grasses reported by Kellems and Church (1998) and Ball *et al.* (2001). The digestibility and nutritive value of grasses are influenced significantly by the stage of maturity (Kellems and Church, 1998). Although bermudagrass in this experiment had its highest CP concentration early in the growing season (Figure 3), herbage mass of CP was low in May, highest around the end of June, and the lowest in early September (data not shown). The lower herbage masses of CP of bermudagrass early in the growing season were due to low herbage growth rather than a low CP concentration but a lower herbage mass of CP late in the growing season was associated with both. Accurate detection of changes in herbage mass of CP would allow more efficient pasture management, such as timing and amount of fertilizer application, adjustment of stocking rate, and determination of timing and amounts of protein supplements fed to livestock grazing these pastures.

Canopy reflectance depends usually on the ground cover of vegetation, canopy architecture and the biochemical composition of plant tissue. Variation in canopy reflectance in the present study was mainly because of the biochemical composition of plant tissue because vegetation completely covered the ground in all genotypes and at all sampling times. Differences in pasture canopy reflectances (centred at 545 nm) between genotypes and among measuring dates (Figure 4) were probably associated with chlorophyll content because leaf chlorophyll concentration is highly and negatively correlated with leaf reflectance at 550 nm (Carter and Spiering, 2002; Zhao *et al.*, 2005). Declines in both the $R_{(NIR)}/R_{(red)}$ and NDVI with sampling dates are probably associated with plant

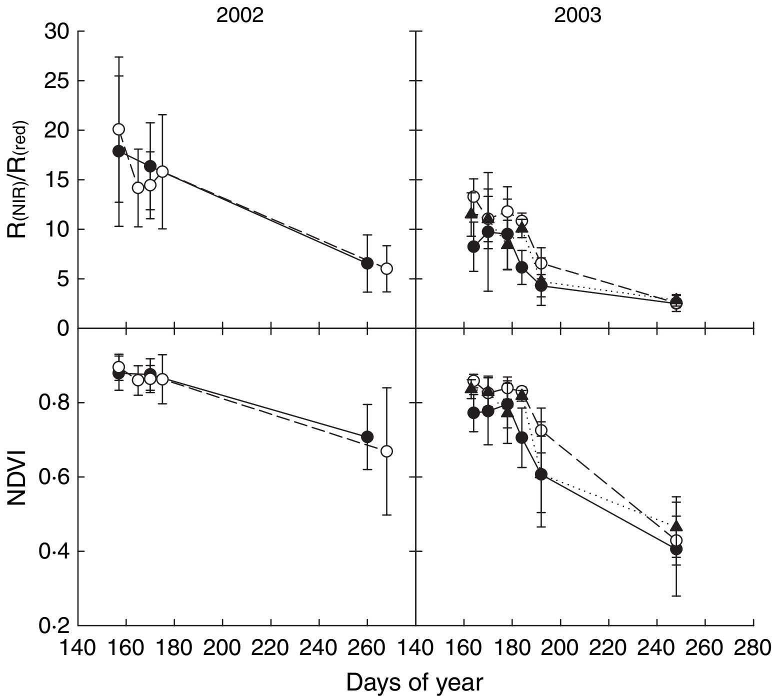

Figure 5 Time-series plots of canopy reflectance ratios in near infrared to red regions ($R_{(NIR)}/R_{(red)}$) and normalized difference vegetation index (NDVI) for Midland (●), Ozarka (○), and 74 × 12-12 (▲) pastures during the 2002 and 2003 growing seasons.

Table 2 Correlation coefficients (r) for neutral-detergent fibre (NDF), acid-detergent fibre (ADF), crude protein (CP) concentration, herbage mass of DM and CP with canopy reflectances in broad wavebands and reflectance indices of $R_{(NIR)}/R_{(red)}$ and normalized difference vegetation index (NDVI)

Waveband	NDF	ADF	CP	Herbage mass of DM	Herbage mass of CP
Blue	0·331***	0·223**	−0·501***	−0·515***	−0·567***
Green	0·188*	−0·051	−0·566***	−0·386***	−0·544***
Red	0·416***	0·290***	−0·586***	−0·535***	−0·641***
RE	−0·459***	−0·370***	0·482***	0·584***	0·662***
NIR	−0·467***	−0·340***	0·546****	0·626***	0·723***
SWIR1	0·270**	0·315***	−0·197*	−0·505***	−0·401***
SWIR2	0·312***	0·393***	−0·188*	−0·491***	−0·405***
$R_{(NIR)}/R_{(red)}$	−0·442***	−0·187*	0·650***	0·669***	0·824***
NDVI	−0·445***	−0·379***	0·561***	0·508***	0·611***

Wavebands include blue (450–520 nm), green (520–600 nm), red (630–690 nm), red-edge (RE, 690–740 nm), near infrared (NIR, 760–900 nm), first short-wave range IR (SWIR1, 1550–1750 nm) and second short-wave IR (SWIR2, 2080–2350 nm) (n = 144). *, $P < 0·05$; **, $P < 0·01$ and ***, $P < 0·001$.

maturity and senescence because leaf:stem ratio (Ball *et al.*, 2001) and canopy chlorophyll content (Kato and Shimuzu, 1987; Zhao *et al.*, 2005) decline as the plants mature. Reflectance indices, such as the $R_{(NIR)}/R_{(red)}$ and NDVI, are important for monitoring plant growth and green biomass (Gamon *et al.*, 1995; Roderick *et al.*, 2000) and the differences in $R_{(NIR)}/R_{(red)}$ and NDVI between years or among genotypes in the present study are consistent with differences in herbage mass described above. Leaf:stem ratio of grass pastures is an important factor affecting diet selection and herbage intake of grazing animals (Smart *et al.*, 2004) because the leaf:stem ratio is closely related to the nutritive value of herbage (Ball *et al.*, 2001). Smart *et al.* (2004) reported that NIRS could be used to estimate leaf:stem ratio of grasses. Although the leaf:stem ratio was not addressed in this study, it may be possible to predict forage leaf:stem ratios by non-destructive measurements of pasture canopy reflectance.

Mutanga *et al.* (2002) investigated canopy reflectance of a tropical grass grown under different nitrogen treatments and concluded that remote sensing of

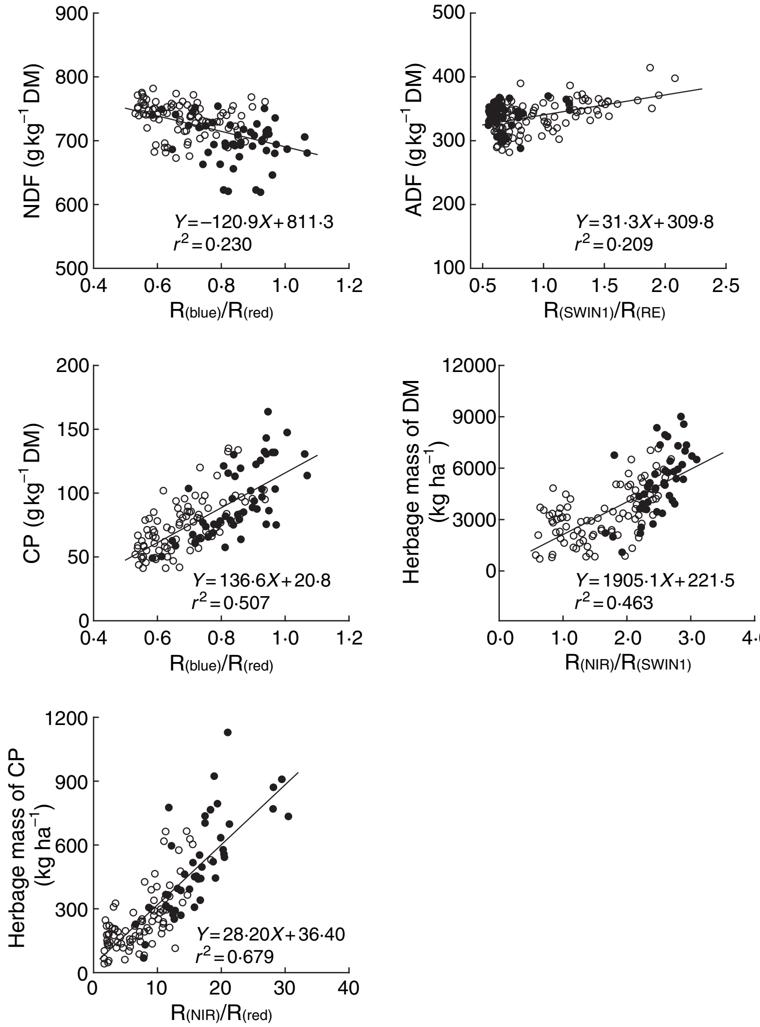

Figure 6 Linear regression of neutral-detergent fibre (NDF), acid-detergent fibre (ADF) and crude protein (CP) concentrations, herbage mass of DM and herbage mass of CP with reflectance ratios having the greatest |*r*| with these variables. Data were pooled across years of 2002 (●) and 2003 (○), plant genotypes and measurement dates ($n = 144$). All the regression equations are significant ($P < 0{\cdot}001$).

canopy chemistry in the visible region might be used to map variation in pasture quality. With herbage grown in pots, Schut *et al.* (2005) found that imaging spectroscopy can provide a means for assessment of herbage mass of DM and for predicting concentrations of several mineral nutrients in herbage. These findings and methodologies are still pending further evaluation under field conditions. There is limited documentation that reports relationships between broad-band reflectance of pasture canopy and nutritive value of herbage, such as NDF and ADF concentrations. In the present study, correlations of canopy reflectance of the pastures in single broad wavebands with the measured nutritive value of bermudagrass herbage were low (Table 2). Using two-band reflectance ratios improved the relationships between canopy reflectance and nutritive value of herbage (Figure 6) compared with the reflectance in single wavebands. Based on linear regression of each measure of nutritive value and the corresponding canopy reflectance ratio that has the greatest |*r*| value (Figure 6), CP concentration of herbage and herbage mass of CP can be estimated using $R_{(blue)}/R_{(red)}$ and $R_{(NIR)}/R_{(red)}$ although the best broad waveband reflectance ratios explained only 0·21–0·23 of the variation in NDF and ADF concentrations. Narrow waveband reflectance and other data analysis methods, such as the band-depth analysis (Kokaly and Clark, 1999) and partial least square regression (Starks *et al.*, 2004; Schut *et al.*, 2005), should be investigated as possible ways to improve relationships between pasture canopy reflectance and nutritive value of herbage and to more accurately estimate the nutritive value of live pastures using canopy reflectance data.

Conclusions

The results indicate that herbage mass productivity and nutritive value of bermudagrass pasture vary considerably among genotypes and between years. Although canopy reflectance in broad wavebands and NDVI were significantly correlated with pasture herbage mass and most measures of nutritive value, these broad waveband reflectance data could only explain a small part of the variation in nutritive value. Two-band reflectance ratios of $R_{(blue)}/R_{(red)}$ and $R_{(NIR)}/R_{(red)}$ can be used for the prediction of CP concentration and herbage mass of CP of standing bermudagrass pastures. Low correlations of NDF and ADF concentrations with canopy broad waveband reflectance or reflectance ratios suggests that it is necessary to develop narrow waveband reflectance algorithms (Starks *et al.*, 2004) for the prediction of nutritive value based on non-destructive measurements of canopy spectral reflectance.

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